Contract Report 579

Ground-Water Quality in the Mahomet Aquifer, McLean, Logan, and Tazewell Counties

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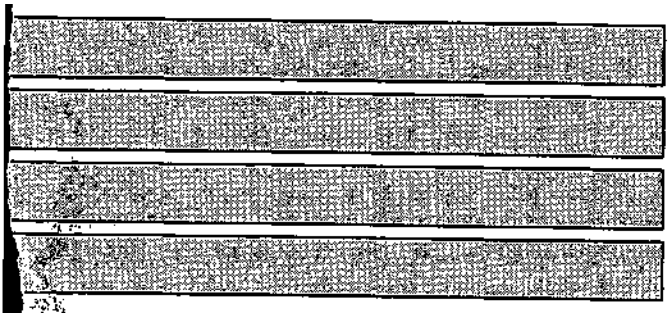
Office of Environmental Chemistry

Prepared for the
Dlinois Department of Energy and Natural Resources

February 1995



Illinois State Water Survey
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A Division of the Illinois Department of Energy and Natural Resources

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ACKNOWLEDGEMENTS

The author thanks several people from the State Water Survey for their contributions to this project:

Steve Wilson, Hydrology Division, for providing information on well locations and construction.

Joe Karny, Hydrology Division, for assistance in collecting samples. (Actually, the author assisted Mr. Karny in sample collection.)

Loretta Skowron, Dan Webb, and Lauren Sievers, Chemistry Division, for chemical analyses.

Saada Hamdy, Chemistry Division, for advice on arsenic determinations, for providing matrix modifier solution, and for the use of her atomic absorption system.

This research was supported by the Environmental Protection Trust Fund, which is administered by the Illinois Department of Energy and Natural Resources.

ABSTRACT

Ground-water samples were collected from wells installed in the Mahomet aquifer in McLean, Tazewell, and Logan Counties. Arsenic had been found in ground water from shallower wells in the study area, so there was concern that ground water from the deeper Mahomet aquifer might also be contaminated with arsenic. The arsenic (As) concentrations in the ground-water samples ranged from undetectable to approximately 100 micrograms per liter ($\mu g\ L^{-1}$) and most As concentrations were less than the current maximum contaminant level (MCL) of 50 $\mu g\ L^{-1}$. Along with arsenic determinations, comprehensive chemical analyses were used to characterize ground-water quality. Most samples had iron concentrations greater than 1 milligram per liter ($mg\ L^{-1}$). Because conventional water treatment processes for iron removal also remove arsenic, it may be feasible to develop a municipal water supply in the Mahomet aquifer within the study area.

INTRODUCTION

The Mahomet aquifer is a source of drinking water for Champaign-Urbana and other communities in east-central Illinois. The hydrologic properties of the aquifer in portions of McLean, Logan, and Tazewell Counties were recently characterized [Wilson et al. In press]. The purpose of that research was to estimate the potential ground-water yield of the aquifer. Arsenic had been found in ground water from private wells near Hopedale, in Tazewell County, in the study area [Holm and Curtiss 1988]. Some of the As concentrations found in that study exceeded the MCL for As set by the U.S. Environmental Protection Agency (EPA) (50 $\mu g\ L^{-1}$). To address concerns that As-contaminated ground water might be found in other parts of the study area, this project was performed to determine whether the water in the Mahomet aquifer did, in fact, contain significant amounts of As.

In addition to As determinations, comprehensive chemical analyses were also performed to characterize the water quality more completely. Because much of the study area is devoted to row-crop cultivation, mostly com and soybeans, the ground-water samples were analyzed for common herbicides. The water samples were also analyzed for several volatile organic compounds (VOCs), since organic solvents and petroleum components are common ground-water contaminants. Sources of VOCs in ground water may include leaking storage tanks (e.g., automobile service stations, storage facilities, and dry cleaners) and pipelines. Several metals (e.g., cadmium and lead) are toxic and their concentrations in drinking water are regulated. Other metals, such as iron and manganese, are "nuisances" (they cause staining of laundry and porcelain), so it would be helpful to know their concentrations in deciding on whether future development is feasible. Therefore, metal concentrations in the water samples were determined.

MATERIALS AND METHODS

Figures 1 and 2 show the study area and the locations of the wells. The curved dotted lines in figure 2 represent the boundaries of the Mahomet-Sankoty aquifer. They show, for example, that on the east side of the study area, McLean lies over the aquifer, while Atlanta does not. The straight dotted lines indicate townships and ranges. Table 1 lists the well depths. The well casings and screens were 2-inch (nominal inner diameter) PVC. In locations where two wells were installed, two holes were drilled; i.e., the wells were not nested in a single hole. All wells were protected by locking security covers [Wilson et al. In press].

Ground water was pumped from the wells using a submersible pump (Grundfos, Clovis, CA). The flow rate was estimated using a stopwatch and a calibrated bucket. The flow rate was approximately 10 liters per minute in most wells. Most of the water was pumped into a bucket and then to waste. The temperature was measured in the bucket using an alcohol-in-glass thermometer. Purging was continued until at least three well volumes had been pumped. A small fraction of the water was directed through a flow-through cell for measuring pH, platinum-electrode potential (Eh), and specific conductance [Garske and Schock 1986]. The pH and specific conductance readings stabilized within the purging period. The Eh never attained a steady value although the rate of change continually decreased. At the end of the purging period, the pH, specific conductance, and Eh were recorded.

After purging, ground-water samples were collected. The flow bypassed the flow-through cell during sample collection. Samples were collected without filtration for determination of nonvolatile organic carbon (NVOC), VOCs, herbicides, and ammonia. The sample tube was then connected to an in-line tangential-flow filter holder (Nuclepore) which held a polycarbonate filter (90 millimeter diameter, 0.1 micrometer pore size, Nuclepore). Samples were collected for determination of alkalinity, anions, metals, and arsenic. The container materials and preservatives used for the various water samples are listed in table 2. The samples were stored in an insulated cooler for transport to the laboratory and then stored at 4°C until analysis. Duplicate samples were collected from one well per sampling trip. One set of sample bottles filled with deionized water was taken along with the other sample bottles to serve as a trip blank, accounting for any contamination during transportation and storage. A filtration blank was collected on one sampling trip, though field filtration blanks were not routinely collected because of the large amount of deionized water needed.

Alkalinity values were determined by titration with standardized acid immediately after sample collection. The endpoint was located by Gran's method [Butler 1982]. All other analyses were performed in the Illlinois State Water Survey laboratories in Champaign. At least two alkalinity titrations were performed for each water sample. The average value for each sample is given in this report. The relative average deviation (difference of duplicates or range of triplicates divided by the average) was less than five percent for all samples.

Arsenic and ammonia concentrations were determined by the author. Arsenic was determined by graphite furnace atomic absorption spectrophotometry (GFAAS) using a palladium-magnesium matrix modifier [Welz et al. 1988]. The detection limit of 3 $\mu g\ L^{-1}$ was estimated as three times the standard deviation of the blank [Keith et al. 1983]. For each set of samples analyzed, at least twenty percent of the samples were run in duplicate, at least ten percent were spiked, and a quality-assessment standard (WS378 #4, U.S. EPA) was run at the beginning and at the end of the analysis. Ammonia concentrations were determined using an ammonia gas-sensitive electrode (Orion) [Greenberg et al. 1992]. It is impossible to estimate a meaningful detection limit for a gas-sensitive electrode. However, the ammonia concentrations of all ground-water samples were within the linear range of the electrode. The ammonia concentrations in the trip blanks were all well below the linear range, i.e., less than one percent of sample concentrations. Therefore, the ammonia determinations were reliable. Every sample for ammonia determination was spiked.

Metals, anions, NVOC, herbicides, and VOCs were determined by a group of chemists that is certified by the Illinois Environmental Protection Agency. Metals were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Anions were determined by ion chromatography. Nonvolatile organic carbon was determined by irradiation with ultraviolet light and persulfate oxidation and measurement of CO_2 by nondispersive infrared absorption [Peyton 1993]. The herbicides atrazine, alachlor, and simazine were determined by liquid-liquid extraction and gas chromatography using a thermionic specific detector (specific for nitrogen and phosphorus). The VOCs listed in table 3 were determined by purge-and-trap gas chromatography with photoionization and Hall electrolytic conductivity detectors.

RESULTS AND DISCUSSION

Table 1 presents the As concentrations in the ground-water samples. Concentrations of other analytes are presented in subsequent tables. Duplicate samples are shown as two entries in the tables. Agreement between duplicate samples was good for all analytes. The tables indicate the samples for which the concentrations were less than the method detection limits (MDLs). The concentrations of several metals and nitrite were below the MDLs in all samples. These analytes are listed in table 4.

Figure 3 shows the frequency distribution of As concentrations. Most of the As concentrations were well below the current MCL for As, although a few samples had concentrations that approached or exceeded the MCL. The As concentrations in all samples except 93-18A, 93-24A, and 93-24B were below the ICP-AES detection limit of 60 $\mu g\ L^{-1}$, which is consistent with the GFAAS results. The As concentration in these three samples was 80 $\mu g\ L^{-1}$. A larger fraction of the shallow wells than of the deep wells had high As concentrations. Figure 4 shows the well locations and relative As concentrations. The spatial distribution of As was rather "spotty". For example, the As concentration in well 93-18 A was 73 $\mu g\ L^{-1}$, while wells 93-13 and 93-22A just to the north and south of 93-18, had As concentrations near the detection limit of 3$\mu g\ L^{-1}$. Similarly,

the As concentration in well 93-24A was almost twice the As MCL, while nearby wells had very low As concentrations.

Panno et al. [1994] compiled water-quality data for the Mahomet aquifer, including the present study area. They present contour maps of the concentrations of several solutes, including As. On their As map, all As concentrations in the present study area are greater than 10 µg L^{-1}. While this is true for many samples listed in table 1, the As concentrations for many other samples were less than the detection limit of 3 µg L^{-1}. Clearly, the distribution of As in ground water is more complex than in the map presented by Panno et al. [1994], which may have been based on a limited data set. This report may be useful in updating their map of As concentrations.

All samples had detectable iron (Fe) and manganese (Mn) (table 5). Most samples had Fe concentrations were greater than 1 mg L^{-1} and some samples had more than 0.2 mg L^{-1} Mn. All samples but 93-1 had detectable ammonia (NH_3); most had NH_3 concentrations greater than 1 mg L^{-1}. The samples were not analyzed for hydrogen sulfide (H_2S), and the characteristic "rotten-egg" odor was undetectable during sample collection. However, the H_2S odor was detected in some samples that had been acidified and stored. Nitrate (NO_3^-) was undetectable in most samples (table 6). The high concentrations of Fe and Mn, high NH_3 and low NO_3^- concentrations, and the odor of H_2S all indicate that oxidation-reduction conditions were suboxic to reducing. Arsenic tends to be more soluble under such conditions than under oxic conditions [Ferguson and Gavis 1972].

The concentrations of aluminum (Al) and titanium (Ti) were fairly low in most samples (table 7), as expected from chemical principles. The Al concentrations in ground water are often near those expected in equilibrium with gibbsite ($Al(OH)_3$). [Drever 1982; Hem 1970] The solubility of gibbsite in the pH range of the study area (table 8) is approximately 2-20 µg L^{-1} [Weslowski 1992]. TiO_2 is quite insoluble. The solubility of TiO_2 in the same pH range is less than 1 µg L^{-1} [Ziemniak et al. 1993]. The Al and Ti concentrations in most samples were in the expected ranges. However, Al and Ti concentrations in some samples were quite high, e.g., up to 6,000 µg L^{-1} Al. If this were truly dissolved Al, then the water would have been oversaturated with respect to gibbsite by almost three orders of magnitude. The most likely explanation for the anomalous Al and Ti concentrations is inadequate filtration. The filter membrane may not have been positioned in the exact center of the filter holder or it may have torn during installation. As a result, particulate matter may have gotten into the samples. Aluminum is a major component of feldspars and clays, which are found in the Mahomet aquifer [Horberg 1953; Willman and Frye 1970], and Ti is a minor component of some minerals. Therefore, if some samples were contaminated with particulate material, then the acid used to preserve the samples dissolved some of the particulate material. Four of the samples for As determination did have visible sediment on the bottoms of the bottles. In other samples, small amounts of colloidal material may have passed through the filter. If particulate material did pass through or by the filter in some samples, it did not appear to affect the As concentrations in most samples. The only sample with high Al and As concentrations was 93-E.

Although the arsenic concentrations did not seem to correlate with either Al or Ti, some of the other anomalous metal concentrations may have resulted from inadequate filtration. For example, sample 92-A, the first sample collected, had high Al and Ti concentrations. It was also the

only sample with detectable beryllium (Be) (1 µg L^{-1}), cobalt (Co) (7 µg L^{-1}), and vanadium (V) (15 µg L^{-1}). It had the highest Pb, nickel (Ni), chromium (Cr), and copper (Cu) concentrations of the few samples in which these metals were detected (table 9).

In addition to the sample from well 92-A, which may have been contaminated by particulate matter, four other samples had Pb concentrations greater than the MCL. However, three of these samples had high Al concentrations, indicating possible filtration problems for these samples as well. Even the highest Pb concentrations were only slightly above the detection limit, so their uncertainty was probably very high. If there is concern about Pb in ground water from these five wells, then they should be resampled and the samples analyzed by a more sensitive method, such as GFAAS.

The major cations in all samples were calcium (Ca), magnesium (Mg), sodium (Na), and ammonium (NH_4^+) (tables 5, 10, and 11). (In the pH range of the study area, most of the ammonia nitrogen is in the form of NH_4^+. The rest is NH_3.) Concentrations of Ca were generally less than 100 mg L^{-1} in agreement with Panno et al. [1994]. The main anion (table 6) was bicarbonate, which accounts for most of the alkalinity in the pH range of the study area [Stumm and Morgan 1981]. The alkalinities in a northwest-to-southeast transect (wells 93-7, 93-18, and 92-A) increased from 381 to 509 mg L^{-1} (as $CaCO_3$) which is consistent with the findings of Panno et al. [1994]. In some samples, chloride (C^{1-})or sulfate (SO_4^{2-}) were significant anions. The C^{1-} concentrations in a west-to-east transect north of Armington (wells 93-17, 93-18, 92-3, 93-19, and 92-B) increased from 3 mg L^{-1} to 73 mg L^{-1}. Concentrations of Na (table 11) followed a similar pattern. This is consistent with Panno et al. [1994] who found steep gradients in Na and C^{1-} concentrations in the eastern part of the present study area Nitrate was only detected in four wells, three of which had NO_3^- concentrations above the MCL (10 mg L^{-1}). Well 93-15 was resampled (table 1) to confirm the high NO_3^- concentration.

The NVOC concentrations ranged from less than 1 mg L^{-1} to almost 40 mg L^{-1} with a median value of approximately 5 mg L^{-1} (table 12). Thurman [1986] found that most ground-water NVOC values are in the range from 0.2 to 15 mg L^{-1} with a median value of 0.7 mg L^{-1}. The relatively high NVOC concentrations are consistent with the suboxic-to-reducing redox conditions found in the present study area. The concentrations of herbicides and VOCs were below detection limits in all samples.

SUMMARY AND CONCLUSIONS

The ground-water quality in the section of the Mahomet aquifer studied in this work is generally good. Arsenic concentrations were high in some samples, but the high concentrations seem to be localized. There was no evidence of contamination by industrial or agricultural chemicals except for high nitrate concentrations in three wells. The concentrations of iron and manganese are typical of ground water. The hardness (the sum of the calcium and magnesium concentrations) is only moderate. The chloride and sulfate concentrations are acceptable. If the aquifer is further developed, then the wells should be installed in areas of low As concentration.

RECOMMENDATIONS

Although the present As MCL is 50 $\mu g\ L^{-1}$, the U.S. EPA may lower the MCL to 20 or even 2 $\mu g\ L^{-1}$ [Pontius 1994]. Arsenic is a suspected carcinogen [Pontius et al. 1994]. However, calculations of the cancer risk from low concentrations of As in drinking water rely on extrapolations of data from areas with extremely high As concentrations. Further research may support the lowering of the MCL or it may support leaving the MCL unchanged.

Arsenic concentrations are lower in some parts of the Mahomet aquifer than in others. If the aquifer is to be developed as a source of potable water, then the wells should be installed in areas of low As concentratioa However, the wells sampled in the present work should first be resampled to confirm their As concentrations. Arsenic concentrations in ground-water samples taken from the same well have been found to vary by orders of magnitude in one year [Nadakavukarnen et al. 1984]. Therefore, sampling over a period of at least one year may be advisable. However, sequential sampling of three wells near Hopedale (in the study area) found only slight temporal changes in dissolved As [Holm and Curtiss 1988].

Although dissolved Fe in water may seem to be a nuisance, it may actually help remove As from the water. Edwards [1994] found that conventional coagulation with $FeCl_3$ removed dissolved arsenate (a common form of As) by sorption and coprecipitation. He developed a model of his data that predicts, e.g., that removal of 2 mg L^{-1} Fe would be expected to reduce an arsenate concentration of 15 $\mu g\ L^{-1}$ to less than 1.5 $\mu g\ L^{-1}$. If the Mahomet aquifer is developed as a potable water source, then bench- and pilot-scale experiments should be performed to test the removal of As during Fe-removal processes. The water should be treated by oxidation and filtration to remove Fe rather than by sequestration to inhibit Fe precipitation. Clearly, the initial As concentration in the raw water should be as low as possible.

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Table 1. Well identification codes, depths, dates sampled, and arsenic concentrations

Well	Description	County	Depth (feet)	Date sampled	As (μg/L)
92-A	N. Atlanta	McLean	330	2 December 1993	3.71
92-G(a)	New Holland	Logan	225	2 December 1993	<3.00
92-G(b)	New Holland	Logan	60	2 December 1993	7.13
92-6	Delavan	Tazewell	287	6 March 1994	6.68
92-6	Delavan	Tazewell	287	6 March 1994	9.50
92-E	Lincoln	Logan	210	6 March 1994	26.49
92-10	Emden	Logan	220	15 March 1994	8.49
92-10	Emden	Logan	220	15 March 1994	11.23
92-8	Hartsburg	Logan	232	15 March 1994	6.18
93-17A	Delavan	Tazewell	239	26 April 1994	<3.00
93-17A	Delavan	Tazewell	239	26 April 1994	3.12
93-17B	Delavan	Tazewell	80	26 April 1994	<3.00
93-22B	Armington	Logan	160	18 May 1994	10.85
93-22B	Armington	Logan	160	18 May 1994	12.95
93-22A	Armington	Logan	311	18 May 1994	3.26
93-13	Hopedale	Tazewell	318	18 May 1994	3.38
92-3B	Armington	Tazewell	60	26 May 1994	44.45
92-3B	Armington	Tazewell	60	26 May 1994	44.44
93-19	Armington	McLean	312	26 May 1994	17.59
93-20	McLean	McLean	311	26 May 1994	26.66

Table 1. (continued)

Well	Description	County	Depth (feet)	Date Sampled	As (μg/L)
92-C	Romine	McLean	315	1 June 1994	19.27
92-C	Romine	McLean	315	1 June 1994	22.64
92-B	McLean	McLean	315	1 June 1994	6.29
93-21	McLean	McLean	325	1 June 1994	4.58
92-7	Hopedale	Tazewell	353	16 July 1994	<3.00
92-7	Hopedale	Tazewell	353	16 July 1994	3.40
92-5	Hopedale	Tazewell	256	16 July 1994	<3.00
93-15	Stanford	McLean	315	16 July 1994	8.25
93-11B	Hopedale	Tazewell	116	22 June 1994	29.78
93-11A	Hopedale	Tazewell	280	22 June 1994	<3.00
93-11A	Hopedale	Tazewell	280	22 June 1994	3.38
93-9	Minier	Tazewell	296	22 June 1994	4.85
92-2A	Minier	Tazewell	286	13 July 1994	9.73
92-2A	Minier	Tazewell	286	13 July 1994	10.90
93-10A	Hopedale	Tazewell	233	13 July 1994	<3.00
93-10B	Hopedale	Tazewell	99	13 July 1994	14.88
93-8	Delavan	Tazewell	256	18 July 1994	22.31
93-8	Delavan	Tazewell	256	18 July 1994	23.51
93-7	Tremont	Tazewell	265	18 July 1994	<3.00
93-3	Mackinaw	Tazewell	269	18 August 1994	<3.00
93-3	Mackinaw	Tazewell	269	18 August 1994	<3.00
93-2	Mackinaw	Tazewell	265	18 August 1994	16.81

Table 1. (concluded)

Well	Description	County	Depth (feet)	Date Sampled	As (μg/L)
93-5	Mackinaw	Tazewell	294	1 September 1994	12.24
93-1	Tremont	Tazewell	215	9 September 1994	<3.00
93-1	Tremont	Tazewell	215	9 September 1994	<3.00
93-6	Tremont	Tazewell	137	9 September 1994	6.89
93-25	Mackinaw	Tazewell	344	9 September 1994	<3.00
93-15	Stanford	McLean	315	13 September 1994	4.03
93-14	Stanford	McLean	334	13 September 1994	9.47
93-24A	Stanford	Tazewell	333	20 September 1994	96.03
93-24A	Stanford	Tazewell	333	20 September 1994	98.77
93-24B	Stanford	Tazewell	122	20 September 1994	81.72
92-3A	Armington	Tazewell	262	20 September 1994	27.27
93-18A	Armington	Tazewell	317	27 September 1994	73.23
93-18B	Armington	Tazewell	160	27 September 1994	38.75
93-18B	Armington	Tazewell	160	27 September 1994	39.80

Table 2. Containers and preservatives used for ground-water samples			
Analyte	Material	Volume (mL)	Preservative
Nonvolatile organic carbon	Glass	125	None
Volatile organic compounds	Glass	500	HCl, 0.05%
Herbicides	Glass	1000	None
Anions	HDPE	250	None
Metals	HDPE	500	HNO_3, 0.05%
Ammonia	HDPE	60	H_2SO_4, 0.1%
Arsenic	HDPE	1000	HCl, 0.05%

Table 3. Volatile organic compounds determined in ground-water samples		
dichlorodifluoromethane	1,1,2-trichloroethane	n-butyl benzene
chloromethane	1,3-dichloropropane	1,2-dichlorobenzene
vinyl chloride	tetrachloroethylene	1,2-dibromo-3-chloropropane
bromomethane	dibromochloromethane	1,2,4-trichlorobenzene
chloroethane	1,2-dibromoethane	hexachlorobutadiene
trichlorofluoromethane	chlorobenzene	naphthalene
1,1-dichloroethene	1,1,1,2-tetrachloroethane	1,2,3-trichlorobenzene
dichloromethane	ethyl benzene	t-1,3-dichloropropene
t-1,2-dichloroethene	m + p xylene	1,4-dichlorobenzene
1,1-dichloroethane	o-xylene	
2,2-dichloropropane	styrene	
c-1,2-dichloroethene	isopropyl benzene	
chloroform	bromoform	
bromochloromethane	1,1,2,2-tetrachloroethane	
1,1,1-trichloroethane	1,2,3-trichloropropane	
1,1-dichloropropene	n-propyl benzene	
carbon tetrachloride	bromobenzene	
1,2-dichloroethane	1,3,5-trimethylbenzene	
benzene	2-chlorotoluene	
trichloroethene	4-chlorotoluene	
1,2-dichloropropane	t-butyl benzene	
bromodichloromethane	1,2,4-trimethylbenzene	
dibromomethane	sec-butyl benzene	
c-1,3-dichloropropene	para-isopropyltoluene	
toluene	1,3-dichlorobenzene	

Table 4. Method detection limits (MDL) for metals that were not detected by ICP-AES in any sample and for nitrite (NO_2^-), which was not detected by IC	
Analyte	MDL
Cd	3
Hg	20
Se	30
Ag	2
Mo	12
Sb	180
Sn	40
Tl	120
Be	1
Co	4
V	6
NO_2^-	30

Note: MDL units are μg L^{-1}.

Table 5. Concentrations of iron (Fe), manganese (Mn), and ammonia (NH_3), platinum-electrode potential (Eh), and hydrogen sulfide (H_2S) odor, (parameters indicating oxidation-reduction conditions) in ground-water samples

Well	Fe	Mn	NH_3	Eh	H_2S Odor
92-A	11.10	0.530	1.6		
92-G(a)	1.68	0.072	0.1		
92-G(b)	4.53	0.112	1.0		
92-6	3.44	0.038	2.1		
92-6	3.42	0.037	2.1		
92-E	3.19	0.100	2.1	155	
92-10	4.83	0.180	1.5	163	
92-10	4.82	1.800	1.2		
92-8	2.89	0.221	0.3	146	
93-17A	3.52	0.056		-142	
93-17A	3.86	0.057			
93-17B	1.16	0.117		-141	
93-22B	2.97	0.037	5.9	-122	
93-22B	2.86	0.036			
93-22A	1.97	0.230	3.3	-173	+
93-13	3.82	0.090	1.4	-170	
92-3B	6.93	2.600	0.5	-161	+
92-3B	7.01	0.260	0.6		
93-19	2.10	0.040	3.3	-170	+
93-20	1.90	0.030	3.5	-170	+
92-C	3.28	0.060	10.5	-131	+
92-C	3.25	0.060	9.7		
92-B	3.93	0.080	8.1	-159	+

Table 5. (continued)					
Well	Fe	Mn	NH_3	Eh	H_2S Odor
93-21	1.72	0.090	5.7	-113	
92-7	4.10	0.100	2.2	-125	
92-7	4.20	0.100	2.4		
92-5	2.89	0.110	1.4	-168	+
93-15	1.52	0.170	23.6	-105	
93-11B	1.92	0.050	3.9	-119	
93-11A	1.71	0.090	2.3	-138	+
93-11A	1.75	0.090	2.3		
93-9	0.24	0.180	6.2	-56	
92-2A	2.55	0.070	4.0	-136	+
92-2A	2.68	0.070	4.1		
93-10A	1.84	0.150	2.9	-124	+
93-10B	1.41	0.040	0.7	-151	+
93-8	1.36	0.210	2.0		
93-8	1.34	0.210	2.0	-116	
93-7	1.60	0.070	2.6		
93-3	1.93	0.210	1.0	-244	+
93-3	2.05	0.210	1.0	-85	
93-2	3.07	0.130	4.5	-103	
93-5	2.24	0.050	3.3	-106	+
93-5	2.25	0.050	3.4		
93-1	0.22	0.160	<0.1	120	
93-1	0.16	0.070	<0.1		
93-6	1.05	0.130	0.4	-125	
93-25	2.23	0.230	4.2	-164	

Table 5. (concluded)					
Well	Fe	Mn	NH_3	Eh	H_2S Odor
93-15	0.44	0.110	39.1	-103	
93-14	3.67	0.210	3.7	-96	
93-24A	4.57	0.040	2.8	-124	+
93-24A	4.70	0.040	3.0		
93-24B	4.49	0.060		-141	
92-3A	4.27	0.200		-140	
93-18A	2.66	0.040	5.0	-105	
93-18B	3.02	0.060	3.6	-89	
93-18B	2.94	0.060	3.6		

Notes: Concentrations of Fe and Mn are in mg L^{-1}.
Concentrations of NH_3 are in mg L^{-1} as N.
Pt electrode potentials are in millivolts vs normal hydrogen electrode.
A "+" in the H_2S odor column indicates the odor was detected in an acidified sample. A blank in this column indicates no odor was detected.
A "<" in the NH_3 column indicates a concentration that was too low to be measured.

Table 6. Concentrations of anions chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), and fluoride (F^-), and alkalinities (Alk) in ground-water samples

Well	Cl^-	NO_3^-	SO_4^{2-}	F^-	Alk
92-A	30.6	<0.02	<0.9	0.4	509.3
92-G(a)	36.1	24.0	60.3	0.2	302.5
92-G(b)	3.6	<0.02	<0.9	0.2	400.0
92-6	3.0	<0.02	<0.9	0.2	
92-6	2.7	<0.02	<0.9	0.2	441.0
92-E	54.0	0.06	2.1	0.4	511.2
92-10	1.6	<0.02	<0.9	0.2	557.0
92-10	1.6	<0.02	<0.9	0.2	
92-8	3.9	<0.02	<0.9	0.2	591.8
93-17A	3.4	<0.02	<0.9	0.2	368.3
93-17A	3.4	<0.02	<0.9	0.2	
93-17B	3.0	<0.02	63.8	0.1	300.7
93-22B	2.2	<0.02	<0.9	0.2	449.8
93-22B	0.5	<0.02	<0.9	0.1	
93-22A	3.1	<0.02	<0.9	0.2	391.0
93-13	3.0	<0.02	<0.9	0.2	409.5
92-3B	4.8	<0.02	51.1	0.2	397.7
92-3B	4.8	<0.02	51.0	0.2	
93-19	57.7	<0.02	<0.9	0.4	470.8
93-20	64.2	<0.02	<0.9	0.4	447.8
92-C	59.3	<0.02	<0.9	0.2	662.5
92-C	59.0	<0.02	<0.9	0.2	
92-B	73.8	<0.02	<0.9	0.3	552.5
93-21	1.6	<0.02	<0.9	0.2	485.3

Table 6. (continued)

Well	Cl^-	NO_3^-	SO_4^{2-}	F^-	Alk
92-7	18.4	<0.02	<0.9	0.1	464.7
92-7	18.3	<0.02	<0.9	0.1	
92-5	6.9	<0.02	<0.9	0.1	407.3
93-15	65.5	19.3	1.7	0.2	527.0
93-11B	5.8	<0.02	4.5	0.1	415.0
93-11A	4.8	<0.02	1.2	0.1	389.8
93-11A	4.9	<0.02	1.2	0.1	
93-9	10.2	<0.02	4.2	0.2	500.3
92-2A	12.9	<0.02	<0.9	0.2	506.2
92-2A	12.9	<0.02	<0.9	0.2	
93-10A	11.6	<0.02	<0.9	0.2	447.8
93-10B	2.5	<0.02	<0.9	<0.1	364.8
93-8	3.6	<0.02	<0.9	0.1	416.0
93-8	3.6	<0.02	<0.9	0.1	
93-7	7.9	<0.02	34.6	0.3	381.0
93-3	37.0	<0.02	1.6	<0.1	493.3
93-3	36.9	<0.02	1.6	<0.1	
93-2	50.1	<0.02	0.9	0.1	492.0
93-5	21.3	<0.02	<0.9	0.2	418.7
93-5	21.5	<0.02	<0.9	0.2	
93-1	20.5	15.7	56.5	<0.1	342.5
93-1	20.6	14.7	56.1	<0.1	
93-6	4.7	<0.02	52.1	<0.1	331.8
93-25	31.5	<0.02	<0.9	0.1	481.3

Table 6. (concluded)					
Well	Cl^-	NO_3^-	SO_4^{2-}	F^-	Alk
93-15	89.4	22.0	11.1	0.1	496.8
93-14	41.8	<0.02	16.3	0.1	458.7
93-24A	1.1	<0.02	<0.9	0.2	393.3
93-24A	1.1	<0.02	<0.9	0.2	
93-24B	1.1	<0.02	<0.9	0.2	385.5
92-3A	2.6	<0.02	<0.9	0.2	366.5
93-18A	1.8	<0.02	<0.9	<0.1	427.0
93-18B	1.8	<0.02	1.1	0.1	412.5
93-18B	1.8	<0.02	1.1	0.1	

Notes: Concentrations of Cl^- and F^- are in mg L^{-1}.
Concentrations of NO_3^- are in mg L^{-1} as N.
Alkalinities are in mg L^{-1} as $CaCO_3$.
A "<" indicates a concentration below the detection limit.
The alkalinity column contains blanks because no samples were collected in duplicate for alkalinity determination.

Table 7. Structural elements. Concentrations of aluminum (Al), titanium (Ti), and silicon (Si) in ground-water samples

Well	Al	Ti	Si
92-A	6.402	0.271	24.8
92-G(a)	1.156	0.039	10.0
92-G(b)	0.037	0.002	10.8
92-6	0.262	0.009	13.0
92-6	0.263	0.009	13.1
92-E	0.256	0.008	8.2
92-10	0.019	<0.001	11.3
92-10	0.020	0.001	11.4
92-8	0.018	<0.001	10.4
93-17A	0.060	0.003	11.2
93-17A	0.039	0.002	11.0
93-17B	0.023	0.001	7.1
93-22B	0.012	0.002	12.6
93-22B	0.012	0.002	12.2
93-22A	0.013	<0.001	10.8
93-13	<0.011	<0.001	10.7
92-3B	0.114	0.005	7.9
92-3B	0.120	0.005	7.9
93-19	0.014	<0.001	8.5
93-20	<0.011	<0.001	7.5
92-C	0.069	0.002	9.6
92-C	0.067	0.003	9.5
92-B	0.184	0.060	9.3
92-31	0.025	<0.001	9.0

Table 7. (continued)			
Well	Al	Ti	Si
92-7	1.333	0.048	13.2
92-7	1.361	0.049	13.3
92-5	0.106	0.003	9.4
93-15	0.519	0.015	9.0
93-11B	0.048	<0.001	6.8
93-11A	0.014	<0.001	8.4
93-11A	0.012	0.002	8.5
93-9	0.027	0.002	7.8
92-2A	0.029	<0.001	9.1
92-2A	0.055	<0.001	9.3
93-10A	<0.011	<0.001	9.1
93-10B	<0.011	0.001	7.9
93-8	0.078	<0.001	10.0
93-8	0.016	<0.001	10.0
93-7	<0.011	<0.001	8.7
93-3	0.025	0.002	7.7
93-3	0.020	0.001	7.7
93-2	1.885	0.077	10.5
93-5	0.044	0.002	8.8
93-5	0.196	0.003	8.7
93-1	0.314	0.009	7.2
93-1	0.187	0.007	7.4
93-6	0.014	0.001	7.6
93-25	0.067	0.003	9.1
93-15	0.112	0.002	6.3

Table 7. (concluded)			
Well	Al	Ti	Si
93-14	0.626	0.029	10.2
93-24A	0.017	0.001	8.5
93-24A	0.025	<0.001	8.7
93-24B	0.015	<0.001	8.7
92-3A	0.273	0.010	10.5
93-18A	0.028	0.002	10.1
93-18B	0.011	0.001	2.9
93-18B	<0.011	<0.001	10.6

Notes: Concentrations are in mg L^{-1}.
A "<" indicates the concentration was less than the detection limit.

Table 8. Values of pH and conductivity in ground-water samples		
Well	pH	Conductivity
92-A	7.19	730
92-G(B)	6.97	735
92-G(A)	7.34	570
92-6	7.09	600
92-E	7.17	740
92-10	7.14	480
92-8	7.24	500
93-17A	7.07	490
93-17B	7.07	435
93-22B	7.08	525
93-22A	7.19	470
93-13	7.40	520
92-3B	7.22	520
93-19	7.44	690
93-20	7.51	730
92-C	7.18	950
92-B	7.42	875
93-21	7.39	660
92-7	7.55	670
92-5	7.74	590
93-15	7.53	950
93-11B	7.61	590
93-11A	7.74	530
93-9	7.70	740
92-2A	7.58	775

Table 8. (concluded)		
Well	pH	Conductivity
93-10A	7.63	640
93-10B	7.69	510
93-8	7.66	580
93-7	7.79	550
93-3	7.45	680
93-2	7.76	750
93-5	7.58	595
93-1	7.06	670
93-6	7.31	550
93-25	7.54	720
93-15	7.87	1100
93-14	7.49	750
93-24A	7.39	515
93-24B	7.53	505
92-3A	7.38	510
93-18A	7.15	555
93-18B	6.95	520

Note: Conductivity units are microsiemens per centimeter.

Table 9. Concentrations of the transition and post-transition elements copper (Cu), lead (Pb), nickel (Ni), zinc (Zn), and cobalt (Co) in ground-water samples

Well	Cu	Pb	Ni	Zn	Co
92-A	0.013	0.023	0.027	0.103	0.007
92-G(a)	0.003	0.015	0.013	0.048	<0.004
92-G(b)	<0.002	<0.014	<0.008	0.031	<0.004
92-6	0.003	<0.014	<0.008	0.017	<0.004
92-6	<0.002	<0.014	<0.008	0.015	<0.004
92-E	<0.002	<0.014	<0.008	0.011	<0.004
92-10	<0.002	<0.014	<0.008	0.020	<0.004
92-10	<0.002	0.018	<0.008	0.021	<0.004
92-8	<0.002	<0.014	<0.008	0.013	<0.004
93-17A	<0.002	<0.014	<0.008	0.014	<0.004
93-17A	<0.002	<0.014	<0.008	0.032	<0.004
93-17B	<0.002	<0.014	<0.008	0.018	<0.004
93-22B	<0.002	<0.014	<0.008	0.008	<0.004
93-22B	<0.002	<0.014	<0.008	0.011	<0.004
93-22A	<0.002	<0.014	<0.008	0.008	<0.004
93-13	<0.002	<0.014	<0.008	0.007	<0.004
92-3B	<0.002	<0.014	<0.008	0.007	<0.004
92-3B	<0.002	<0.014	<0.008	0.024	<0.004
93-19	<0.002	<0.014	<0.008	0.004	0.005
93-20	<0.002	<0.014	<0.008	0.006	<0.004
92-C	<0.002	<0.014	0.009	0.065	<0.004
92-C	<0.002	<0.014	<0.008	0.025	<0.004
92-B	<0.002	<0.014	<0.008	0.009	<0.004
93-21	<0.002	<0.014	<0.008	0.255	<0.004

Table 9. (continued)

Well	Cu	Pb	Ni	Zn	Co
92-7	<0.002	0.015	0.011	0.139	<0.004
93-11B	0.003	<0.014	<0.008	0.333	<0.004
93-11A	<0.002	<0.014	<0.008	0.087	<0.004
93-11A	<0.002	<0.014	<0.008	0.019	<0.004
93-9	<0.002	<0.014	0.009	0.009	<0.004
92-2A	<0.002	<0.014	<0.008	0.101	<0.004
92-2A	0.004	<0.014	<0.008	0.912	<0.004
93-10A	<0.002	<0.014	<0.008	0.051	<0.004
93-10B	<0.002	<0.014	<0.008	0.027	<0.004
93-8	<0.002	<0.014	0.010	0.327	<0.004
93-8	<0.002	<0.014	<0.008	0.048	<0.004
93-7	<0.002	<0.014	<0.008	0.027	<0.004
93-3	<0.002	<0.014	<0.008	0.029	<0.004
93-3	<0.002	<0.014	<0.008	0.088	<0.004
93-2	<0.002	<0.014	0.009	0.024	<0.004
93-5	<0.002	<0.014	<0.008	0.028	<0.004
93-5	<0.002	<0.014	<0.008	0.072	<0.004
93-1	0.003	<0.014	<0.008	0.275	<0.004
93-1	0.002	<0.014	0.017	0.042	<0.004
93-6	<0.002	<0.014	0.015	0.020	<0.004
93-25	<0.002	<0.014	<0.008	0.020	<0.004
93-15	<0.002	<0.014	<0.008	0.513	<0.004
93-14	<0.002	<0.014	0.010	0.090	<0.004
93-24A	<0.002	<0.014	<0.008	0.077	<0.004
93-24A	<0.002	<0.014	<0.008	0.664	<0.004

Table 9. (concluded)					
Well	Cu	Pb	Ni	Zn	Co
93-24B	<0.002	<0.014	<0.008	0.039	<0.004
92-3A	<0.002	<0.014	<0.008	0.040	<0.004
93-18A	<0.002	<0.014	<0.008	0.355	<0.004
93-18B	<0.002	<0.014	<0.008	0.113	<0.004
93-18B	<0.002	<0.014	<0.008	0.017	<0.004

Notes: Concentrations are in mg L^{-1}.
A "<" indicates a concentration below the detection limit.

Table 10. Concentrations of the alkaline earth elements calcium (Ca), magnesium (Mg), strontium (Sr), and barium (Ba) in ground-water samples

Well	Ca	Mg	Ba	Sr
92-A	76.6	40.1	0.236	0.507
92-G(a)	109.0	58.0	0.103	0.173
92-G(b)	85.5	39.1	0.253	0.296
92-6	83.6	42.3	0.132	0.275
92-6	83.5	42.4	0.132	0.275
92-E	74.2	37.6	0.605	0.582
92-10	81.2	32.7	0.278	0.179
92-10	81.2	32.8	0.279	0.179
92-8	75.3	33.8	0.153	0.138
93-17A	76.1	34.2	0.126	0.281
93-17A	75.1	33.8	0.124	0.277
93-17B	81.4	35.7	0.051	0.112
93-22B	82.9	40.4	0.172	0.346
93-22B	80.3	39.1	0.167	0.336
93-22A	77.2	36.0	0.129	0.312
93-13	79.2	34.4	0.220	0.283
92-3B	94.4	43.5	0.133	0.195
92-3B	94.7	43.7	0.134	0.197
93-19	70.5	32.6	0.493	0.690
93-20	63.0	27.5	0.620	0.540
92-C	88.5	40.6	0.406	0.604
92-C	87.2	40.0	0.397	0.591
92-B	73.9	37.5	0.344	0.752
93-21	83.7	32.8	0.314	0.492

Table 10. (continued)				
Well	Ca	Mg	Ba	Sr
92-7	80.7	38.2	0.239	0.408
92-7	81.1	38.5	0.239	0.410
92-5	69.1	34.6	0.274	0.332
93-15	75.5	39.3	0.266	0.709
93-11B	70.2	34.5	0.170	0.498
93-11A	67.3	34.5	0.198	0.436
93-11A	68.9	35.3	0.203	0.447
93-9	71.1	41.7	0.137	0.675
92-2A	72.8	34.3	0.490	0.596
92-2A	75.7	35.1	0.498	0.603
93-10A	72.1	35.4	0.236	0.467
93-10B	67.0	37.2	0.069	0.201
93-8	70.7	38.6	0.243	0.375
93-8	70.3	38.4	0.244	0.372
93-7	79.7	41.0	0.241	0.586
93-3	85.2	37.5	0.280	0.276
93-3	85.6	37.7	0.282	0.277
93-2	70.4	36.8	0.225	0.602
93-5	65.4	31.8	0.235	0.481
93-5	65.4	31.8	0.235	0.483
93-1	99.8	43.5	0.051	0.105
93-1	102.4	44.9	0.052	0.106
93-6	81.5	37.4	0.062	0.117
93-25	75.2	36.5	0.299	0.537
93-15	56.1	30.2	0.367	0.567

Table 10. (concluded)				
Well	Ca	Mg	Ba	Sr
93-14	82.3	41.8	0.179	0.532
93-24A	67.9	32.9	0.144	0.585
93-24A	70.3	33.7	0.149	0.601
93-24B	69.9	33.5	0.144	0.610
92-3A	69.1	32.6	0.149	0.368
93-18A	80.9	38.6	0.095	0.316
93-18B	81.8	39.2	0.088	0.286
93-18B	80.1	38.1	0.087	0.282

Note: Concentrations are in mg L^{-1}.

Table 11. Concentrations of the alkali metals sodium (Na), potassium (K), and lithium (Li) in ground-water samples

Well	Na	K	Li
92-A	103.1	4.15	0.014
92-G(a)	7.5	0.34	0.005
92-G(b)	18.4	1.51	0.009
92-6	23.0	2.25	0.010
92-6	23.0	2.21	0.010
92-E	71.1	2.13	0.008
92-10	14.1	0.91	0.007
92-10	14.2	0.93	0.007
92-8	12.6	0.65	0.006
93-17A	14.3	1.25	0.006
93-17A	14.1	1.18	0.006
93-17B	6.3	0.35	0.003
93-22B	18.9	2.65	0.010
93-22B	18.2	2.60	0.009
93-22A	15.3	1.40	0.007
93-13	23.5	1.52	0.012
92-3B	6.9	<0.24	0.002
92-3B	7.0	<0.24	0.003
93-19	94.6	1.67	0.005
93-20	102.9	1.97	0.006
92-C	135.3	1.75	0.013
92-C	132.7	2.08	0.014
92-B	117.5	2.55	0.006
93-21	45.5	1.16	0.005

Table 11. (continued)			
Well	Na	K	Li
92-7	39.3	1.84	0.008
92-7	39.6	1.82	0.008
92-5	28.0	1.77	0.009
93-15	98.9	2.43	0.008
93-11B	22.4	1.82	0.003
93-11A	24.6	2.17	0.008
93-11A	25.3	2.13	0.008
93-9	74.8	2.23	0.006
92-2A	88.2	2.23	0.007
92-2A	90.5	2.15	0.007
93-10A	54.4	1.45	0.006
93-10B	13.7	0.49	0.002
93-8	26.7	1.48	0.009
93-8	26.0	1.36	0.009
93-7	18.1	1.02	0.005
93-3	59.5	2.98	0.006
93-3	60.0	3.06	0.006
93-2	79.2	3.52	0.009
93-5	47.9	1.80	0.005
93-5	48.2	1.84	0.005
93-1	6.3	2.11	0.004
93-1	6.6	1.82	0.006
93-6	5.4	0.44	0.009
93-25	67.1	2.28	0.012
93-15	118.3	3.17	0.011

Table 11. (concluded)			
Well	Na	K	Li
93-14	47.6	1.82	0.009
93-24A	17.4	1.74	0.007
93-24A	18.3	1.33	0.003
93-24B	17.7	1.32	0.003
92-3A	14.7	1.22	0.006
93-18A	10.8	1.51	0.007
93-18B	10.2	2.17	0.009
93-18B	9.8	1.56	0.007

Note: Concentrations are in mg L^{-1}.
A "<" indicates the concentration was less than the detection limit.

Table 12. Concentrations of phosphorus (P), sulfur (S), selenium (Se), and nonvolatile organic carbon (NVOC) in ground-water samples

Well	P	S	Se	NVOC
92-A	0.160	0.380	<0.03	
92-G(a)	<0.15	20.200	<0.03	
92-G(b)	<0.15	<0.11	<0.03	
92-6	<0.15	<0.11	<0.03	13.6
92-6	<0.15	0.130	<0.03	13.3
92-E	0.170	0.610	<0.03	12.2
92-10	0.190	<0.11	<0.03	7.0
92-10	0.260	<0.11	<0.03	7.9
92-8	<0.15	<0.11	<0.03	2.8
93-17A	<0.15	<0.11	<0.03	1.9
93-17A	<0.15	0.230	<0.03	1.8
93-17B	<0.15	19.400	<0.03	0.5
93-22B	<0.15	<0.11	<0.03	3.1
93-22B	<0.15	<0.11	<0.03	3.2
93-22A	0.170	<0.11	<0.03	1.9
93-13	0.240	<0.11	<0.03	2.2
92-3B	0.240	16.500	<0.03	1.1
92-3B	0.210	16.700	<0.03	1.0
93-19	0.440	0.130	<0.03	5.1
93-20	0.320	0.150	<0.03	5.4
92-C	0.390	0.290	<0.03	9.2
92-C	0.320	0.250	<0.03	9.5
92-B	0.300	0.260	<0.03	6.8
93-21	0.290	0.420	<0.03	4.8

Table 12. (continued)

Well	P	S	Se	NVOC
92-7	<0.15	0.110	<0.03	3.2
92-7	0.160	<0.11	<0.03	3.1
92-5	<0.15	<0.11	<0.03	1.9
93-15	<0.15	0.630	<0.03	19.9
93-11B	<0.15	1.560	<0.03	3.1
93-11A	<0.15	0.230	<0.03	2.5
93-11A	<0.15	0.230	<0.03	2.1
93-9	<0.15	1.470	<0.03	5.8
92-2A	0.210	0.120	<0.03	5.1
92-2A	0.300	0.120	<0.03	5.0
93-10A	0.200	<0.11	<0.03	4.0
93-10B	<0.15	<0.11	<0.03	
93-8	<0.15	<0.11	<0.03	2.5
93-8	0.150	<0.11	<0.03	2.7
93-7	0.200	11.700	<0.03	1.3
93-3	<0.15	<0.11	<0.03	5.6
93-3	<0.15	<0.11	<0.03	5.8
93-2	0.290	<0.11	<0.03	7.5
93-5	0.170	<0.11	<0.03	4.8
93-5	0.170	<0.11	0.04	8.3
93-1	<0.15	16.100	<0.03	3.6
93-1	<0.15	17.200	0.04	3.6
93-6	<0.15	15.900	<0.03	3.6
93-25	0.180	0.150	<0.03	9.7
93-15	<0.15	3.870	<0.03	39.7

Table 12. (concluded)				
Well	P	S	Se	NVOC
93-14	0.250	5.180	<0.03	10.2
93-24A	0.250	<0.11	<0.03	7.1
93-24A	0.240	0.110	<0.03	7.0
93-24B	0.240	<0.11	0.04	7.0
92-3A	<0.15	<0.11	<0.03	4.7
93-18A	<0.15	0.250	<0.03	6.6
93-18B	<0.15	0.330	<0.03	3.1
93-18B	<0.15	0.390	<0.03	6.2

Notes: Concentrations of P, S, and Se are in mg L^{-1}.
Concentrations of NVOC are in mg C L^{-1}.
A "<" indicates the concentration was less than the detection limit.

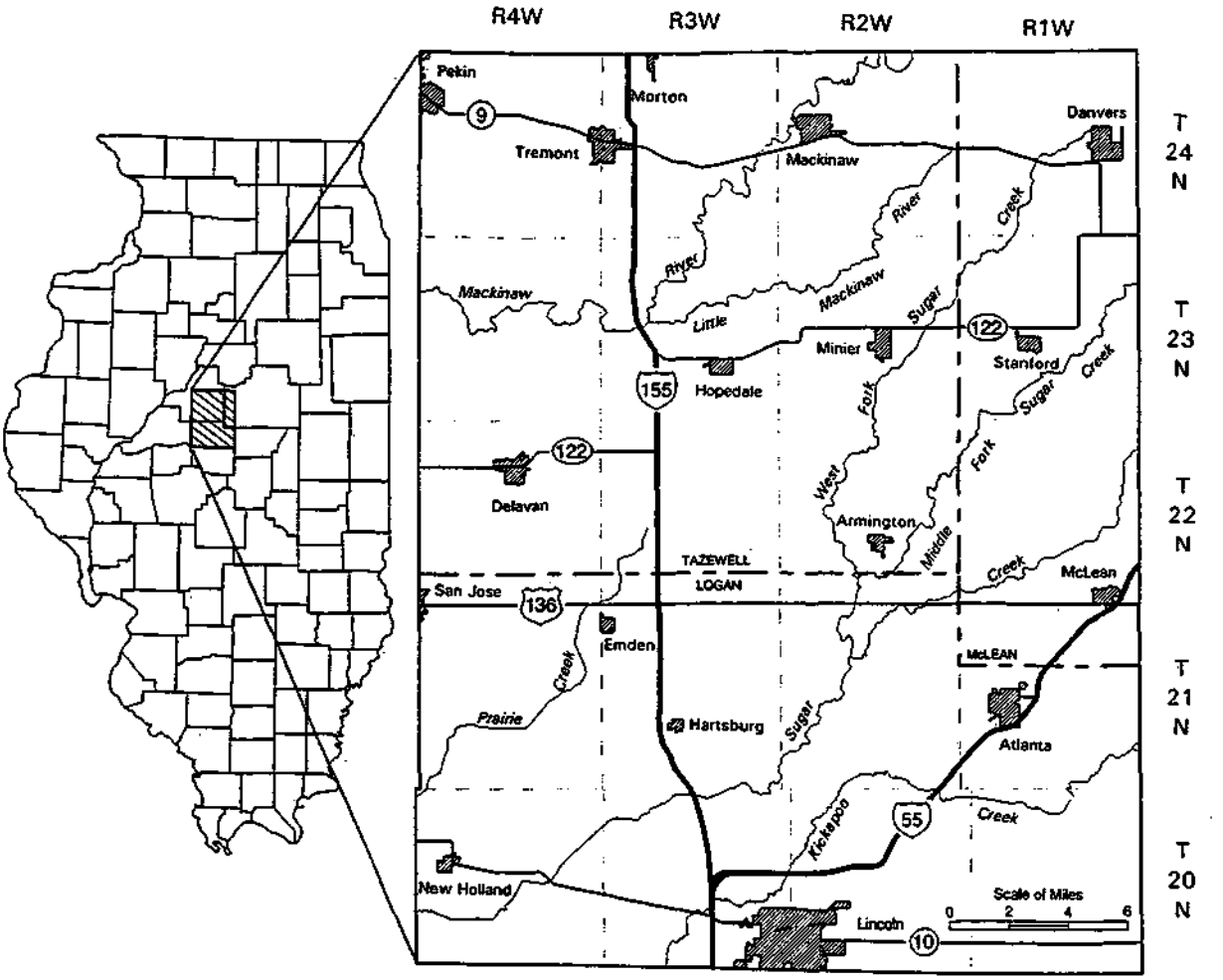

Figure 1. Location of the study area (Wilson et al. In press)

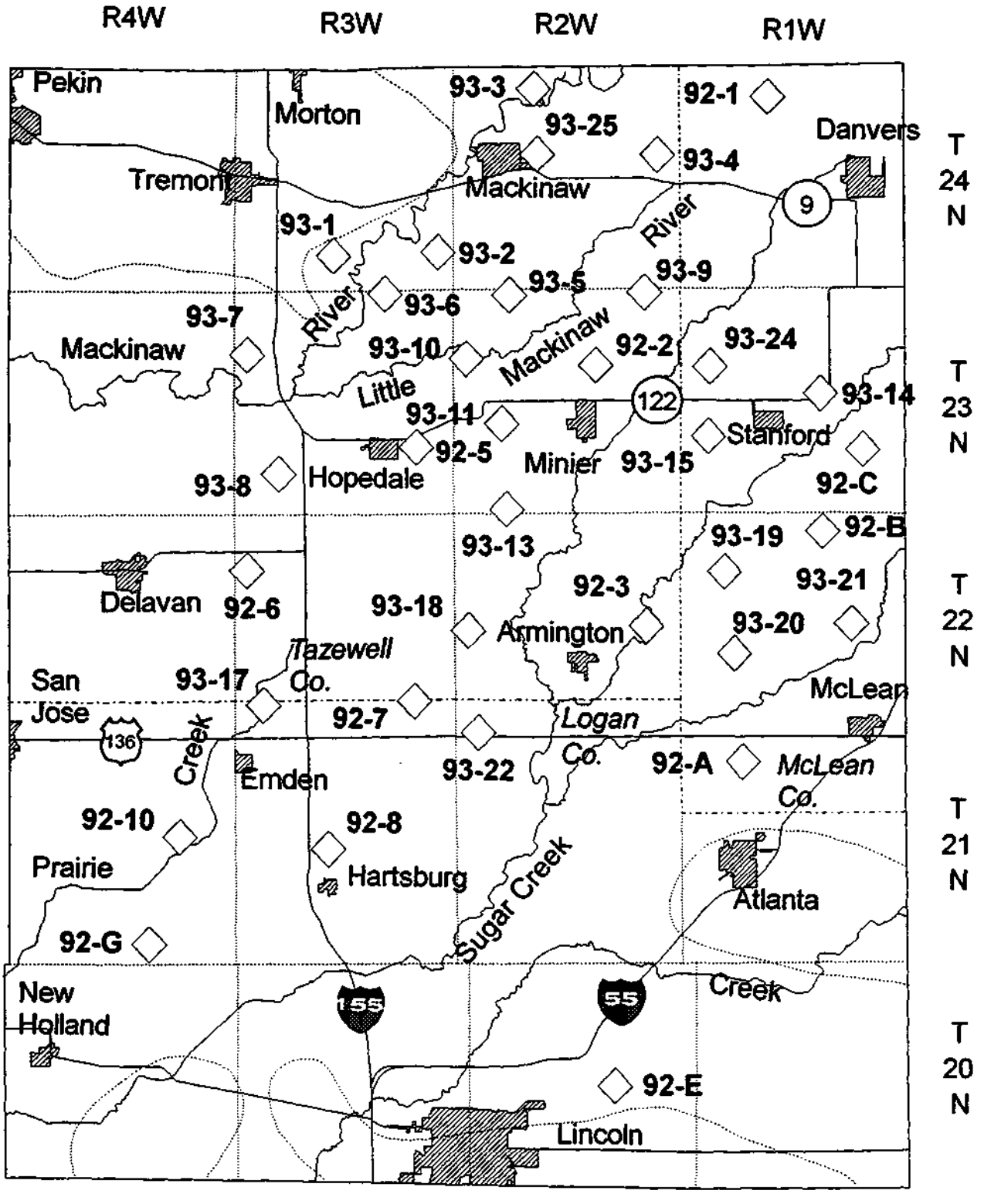

Figure 2. Location of wells in the study area (adapted from Wilson et al. In press)

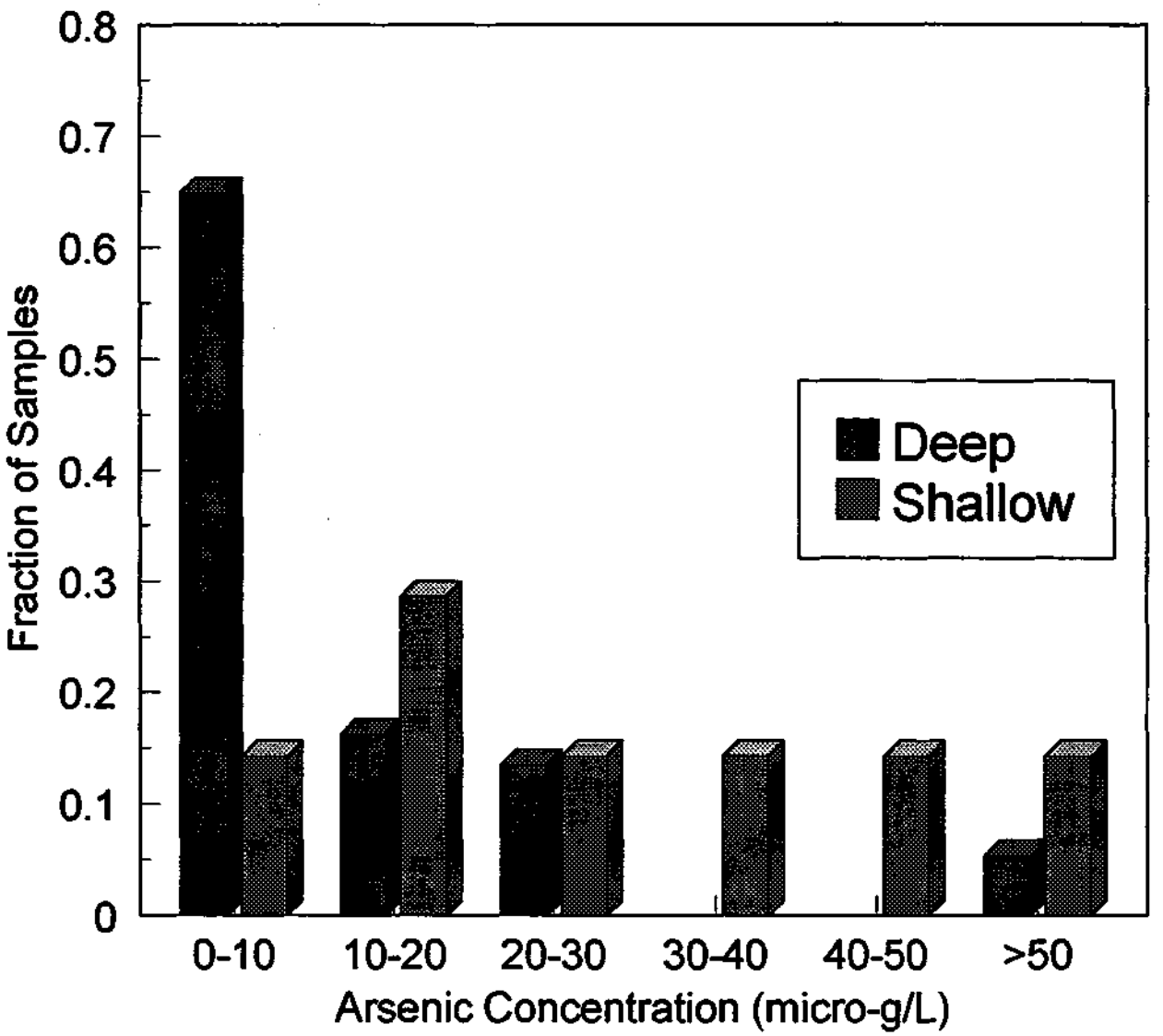

Figure 3. Frequency distribution of arsenic concentrations in ground water

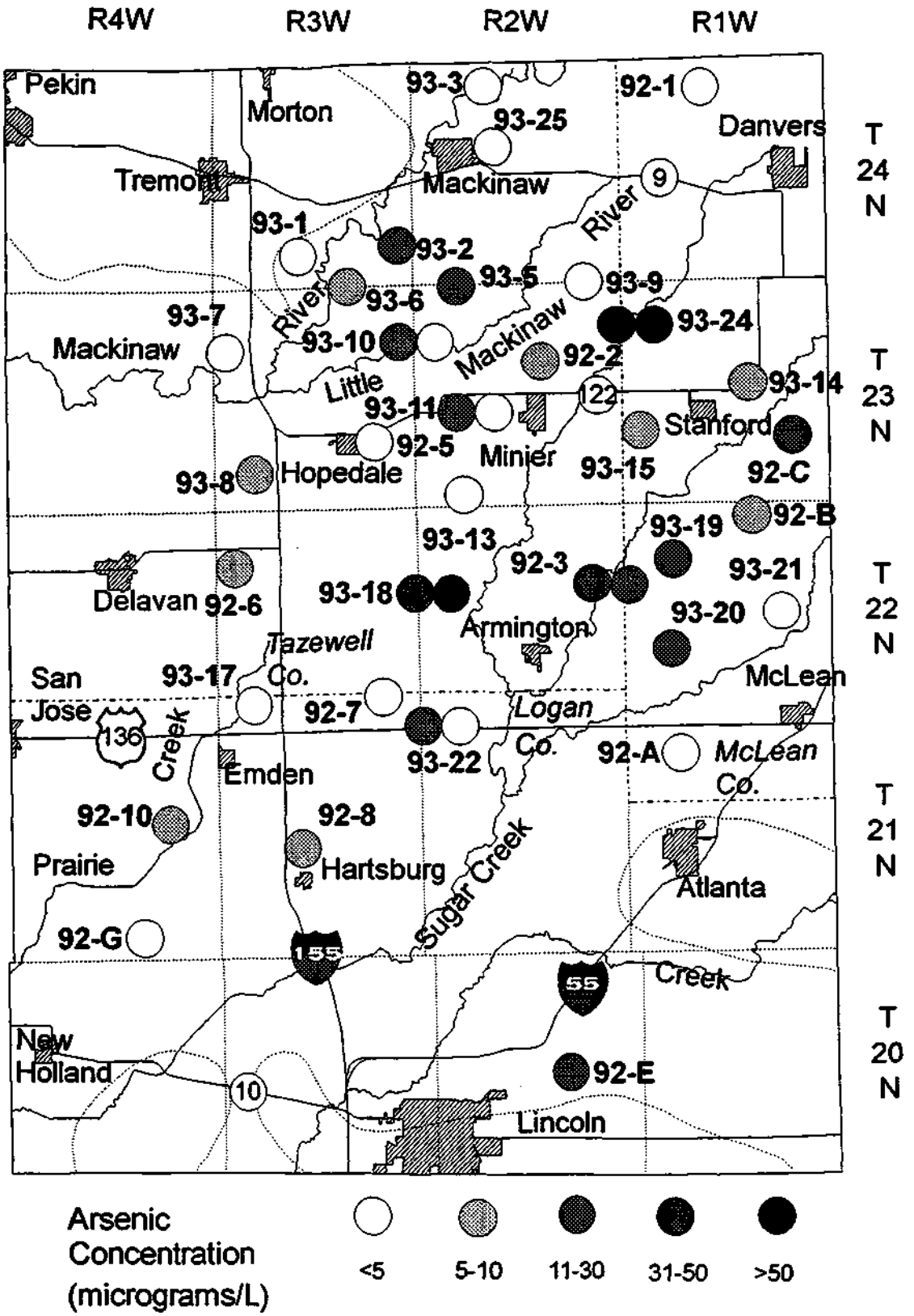

Figure 4. Map of arsenic concentrations (adapted from Wilson et al. In press)